Scientific Objective 4: Meteorological Data

The purpose of scientific objective 4 is to augment the meteorological data base.

Introduction

Although it is often thought that modern society is becoming less vulnerable to the weather, in many respects the reverse is true. For example, weather is still the dominant factor in determining annual changes in global and regional food production, a fact made more important by recent declines in grain reserves. (These reserves now barely cover annual variations in production caused by weather.) In addition, many economies (including our own) are becoming increasingly dependent on international transport of products and resources; furthermore, an increasing portion of oil and other resources is being derived from off-shore operations. As a result, changes in weather and sea state have become more important in determining the performance of related sectors of the economy. These are but three examples of the many aspects of modern societies and economies that are sensitive to the weather. Another contributing factor is the growing scale of man's activities, which have reached the point of inadvertently affecting the weather. All of these trends have increased the importance of accurate weather measurements and predictions, not only in major population centers but also in more remote areas such as ocean shipping lanes and major agricultural regions (Committee on Atmospheric Sci., Natl. Res. Council, 1977).

In recent decades the advent of weather radar, weather satellites, and increasingly powerful computers has led to tremendous advances in our ability to monitor weather and to understand it. However, the relatively modest accompanying gains in forecasting skill (Phillips, 1976; Halem, 1976; Tracton and McPherson, 1977; Baer and Boudra, 1977) point to the fact that much room for improvement remains. For example, improved warnings of severe storms and increased skill in predicting weather statistics in specific growing regions and seasons could yield benefits measured in the hundreds of millions of dollars (e.g., Committee on Atmospheric Sci., Natl. Res. Council, 1977).

Improvements in the observational data base, along with improvements in numerical prediction models and computers, are thought to hold the key to improved skill in weather prediction. Careful consideration of these factors has been made, and several studies have specified resolutions and accuracies for various observations that are considered necessary for fundamental improvements in forecast accuracy (e.g., The Physical Basis of Climate and Climate Modelling in 1974, U.S. Committee for Global Atmospheric Res. Program in 1978, and Proposed NASA Contribution to the Climate Program in 1977).* These requirements are summarized in table I. The parameters in the body of the table describe the needs for global or hemispheric numerical weather prediction models. As noted above, current global prediction models have not benefitted

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*These documents are not formally published and are therefore not in the reference list.

significantly from the uses made of satellite weather data, particularly remotely sensed temperature soundings. This is partly due to the skillful use of all the older types of weather data, including land, ship, and aircraft reports. The current Northern Hemisphere satellite sounding data set adds only small nuances to the conventional data set. Although the satellite data can have a large impact on individual situations, current global prediction models are usually insensitive to the small nuances in initial state that the satellites provide (Phillips, 1976; Tracton and McPherson, 1977). Also, intercomparison of models shows that differences in the analyses and forecasts of different models can be far greater than the differences produced by satellite data. Hence, model errors can still dominate, and this prevents a general demonstration of a positive impact of satellite data on global-scale or hemispheric-scale numerical prediction.

Partially as a result of this situation, fine-mesh prediction models are now being developed to give improved short-range (1 to 2 days) predictions, particularly of weather phenomena of interest to the public - namely winds, rain, thunderstorms, snow, etc. (e.g., Shuman, 1978). Figure 1 shows the horizontal area and grid spacing for several types of fine-mesh models in comparison to the hemispheric model of the U.S. National Meteorological Center (NMC). The fine-mesh models require initial data with finer spatial and temporal resolution than do the global models, and perhaps with better accuracy. (See the footnote in table I for details). Also, the fine-mesh models are sensitive to factors not important for the large-scale circulation. These include moisture, latent heat release, radiation effects of clouds, and vertical wind components. Current satellite observing systems cannot measure all of these quantities to the required accuracies and resolutions. However, improved satellite instruments, including lidar, have the potential to make the required measurements, so that satellite data will become increasingly more important to numerical weather prediction as time goes on.

Specific Problems

The following sections discuss the basis for the specific requirements in table I and the ability of lidar and other sensors to satisfy them. The section "Summary of Needs and Expected Capabilities" summarizes the requirements and their relation to the expected performance of various lidar measurements. (See also appendix A.)

Temperature.- The development of satellite temperature sounders and their application in understanding and forecasting weather have been and continue to be a major thrust of the NASA meteorology program. The emphasis on the development of current sounders such as the Vertical Temperature Profile Radiometer (VTPR), the High Resolution Infra-Red Sounder (HIRS), and the Scanning Microwave Sounder (SCAMS) provides ample evidence of this thrust. In the mid- and high-latitude section of table I, temperatures are listed first (before winds) because in these latitudes it has been common practice to derive winds from temperatures using balance relationships. (Note, however, the discussion in the "Winds" section.)

General circulation models have now developed to the point where data at as many as seven independent tropospheric levels are required, whereas even the most advanced passive sounder currently under study is expected to provide no more than four independent levels. In addition, evaluation studies of sounding accuracy by both the National Meteorological Center and the Goddard Institute for Space Studies show that current passive sounding techniques can provide an accuracy of only about 1.5 to 3.5 K, depending upon level. Figure 2 shows an example of the result of this type of evaluation study. In the Northern Hemisphere this accuracy is not sufficient to produce more than small improvements in the forecast accuracy achieved on the basis of surface, radiosonde, and aircraft measurements alone.

Hence, the requirements for temperature profiles specified in table I markedly exceed the present capabilities of passive temperature sounders. Table I thus clearly establishes a need for sounders with greatly improved accuracy relative to current capabilities (1 K vs. 1.5 to 3.5 K). With regard to accuracy, it should also be noted that thin clouds and aerosol layers can introduce substantial errors into passive temperature soundings. However, the extent of these errors and the best methods to correct them have not been satisfactorily established because of (1) the approximate theoretical treatment of cloud and aerosol layers and (2) the current difficulty in documenting thin cloud and aerosol layer height, density, or even occurrence within the passive profiler field of view. Differences of 3 to 4 K and larger between satellite and radiosonde temperature profiles have been observed near the antarctic tropopause (Asgeirsson and Stanford, 1977); it is possible that subvisible cirrus clouds are responsible for these differences, but without further data this is only speculation.

Lidar measurements from space could be used to improve temperature soundings in two ways. In the near future, they could be used to document cloud and aerosol layer heights and densities within the FOV of co-aligned passive profilers. The resulting data set could clarify the effects of particulate layers as a function of location and season and lead to improved analysis methods or instrumentation, which would improve the accuracy of the data product produced by passive sounders. Also, for thick clouds, combining an infrared window measurement with a lidar height measurement could yield the temperature at a well-defined height. With further development it appears that lidar differential absorption or Doppler measurements could provide direct measurements of the complete temperature profile with extremely high vertical resolution. In addition, the use of the lidar technique will allow the temperature of specified layers to be measured in a direct manner, rather than requiring the use of inversion techniques as must currently be done in order to use the data from passive profilers. Finally, mathematical analysis indicates that a lidar temperature profile experiment could meet the 1 K temperature accuracy requirement while simultaneously meeting the vertical resolution requirement of 2 km.

Winds.- In the tropics, horizontal wind is considered the most important observational variable because the synoptic-scale temperature and pressure gradients are weak; hence, the wind is only weakly coupled to the mass field and may not be satisfactorily derived from other parameters. Moreover, in extratropical regions, even though geostrophic wind can be derived from other parameters, nongeostrophic wind components near the tropopause and in the lower

levels are important for the diagnosis and prediction of weather development, and these cannot be derived from the temperature field alone. Thus there is a need for horizontal wind measurements at all latitudes, but the need is greatest in the tropics. There is also a need for vertical-wind measurements and their associated regions of convergence, divergence, and instability. These needs are summarized in table I.

Wind information is currently derived from radiosondes launched once every 12 hours from points about 350 km apart in developed countries, with much larger gaps over the oceans. Cloud motions derived from satellite photographs are another source of wind data, but this method, though very valuable, is limited as it cannot provide the wind field at cloud-free levels or locations. There are also questions regarding the possible differences between apparent cloud motions and the true wind and, more fundamentally, difficulties with assigning heights to the derived cloud-motion vectors. The cloud-height problem is especially difficult for cirrus clouds (typical errors of 1 to 2 km or more - see Shenk et al., 1975; Reynolds and Vonder Haar, 1977; Minzner et al., 1978) and for cumulus clouds that penetrate the tropopause and may have temperatures that differ from their surroundings. (See also "Clouds" below.) With regard to the vertical-wind component, it should be noted that there is currently no satellite method for measuring it.

Space-borne lidar has the potential to improve wind measurements in two main ways. In the near term, cloud-top height measurements could be made to well within the accuracy specified in table I, and this, combined with concurrent passive radiometric data, could aid in testing and refining passive height-assignment strategies. (Current tests of passively derived heights are not so direct as those permitted by space-borne lidar.) In the longer term, Doppler lidar measurements could possibly provide a direct measure of both vertical and horizontal winds in all areas unobscured by thick clouds.

Pressure.- The pressure field is the most fundamental variable in weather prediction and atmospheric circulation studies. Surface pressure and 500 mb heights are used by the operational meteorologist to determine mass movement; the three-dimensional pressure field is also the principal variable used in general circulation models for mid-range and long-range forecasting. It may be noted that the pressure profile can be used directly to specify both the temperature profile and the "balanced" wind. In contrast, the derivation of a pressure profile from a temperature profile is not possible without specifying pressure at a reference height.

Currently, remote-sensing techniques for the direct measurement of the pressure profile and even for the surface pressure have not yet been developed; moreover, the lack of an accurate pressure reference level hinders derivation of pressure profiles from radiometrically sensed temperature profiles. As a result, measurements of the pressure profile are available only at radiosonde locations and where satellite temperature profiles and a surface pressure measurement coincide.

The lidar technique combined with the method of differential absorption could permit the direct measurement of either the surface pressure (using ground-based reflection) or cloud pressure heights (using cloud-top returns).

Specification of a reference pressure and the height at which the reference pressure is obtained is a basic requirement of the NASA climate plan as well as for the GARP program. The requirements for this measurement for the above programs are an accuracy of 0.3 percent and a horizontal resolution of 500 km, which it is believed could be met or exceeded by a lidar measurement.

The lidar-measurement technique may also be used in conjunction with returns from aerosol and molecular scattering to obtain a direct measurement of the pressure profile in the lower troposphere. For this measurement, mathematical analysis shows that accuracies in the range of 0.2 percent for altitudes less than 2 km, and accuracies of better than 0.4 percent for altitudes up to 5 km, are potentially obtainable with a vertical resolution of 1 km and a horizontal resolution of 500 km. This measurement of the pressure profile would provide information which must currently be derived from a combination of measurements of the temperature profile, at much poorer vertical resolution, and ground-based measurements of surface pressure.

Humidity.- Until recently, atmospheric humidity (whether in vapor or liquid form) has not been considered very important as initial data for global numerical weather prediction. However, the thrust to develop fine-mesh prediction models has changed this, both because of the importance of clouds and rain to mesoscale processes and because humidity is a very sensitive indicator of horizontal convergence or divergence (particularly in the lower atmosphere). The divergence patterns in turn relate to vertical air currents that are important in energy transformations, which are involved in the formation of storms such as cyclones, squall lines, and hurricanes. Another potential application of humidity data from geosynchronous satellites is in the determination of winds in cloud-free areas (Endlich et al., 1972). This method is similar to tracking clouds to determine winds since humidity patterns on isentropic surfaces are tracers of air motions. Data of sufficient accuracy and detail to permit application of this method have been obtained very recently by the European geosynchronous satellite Meteosat and are currently being studied. (See the example in fig. 3.) Although microwave instruments flown on recent satellites (e.g., the ESMR on Nimbus 5 and the SCAMS on Nimbus 6) have given promising results in measuring humidity, the vertical resolution has not been sufficient to meet the requirements of table I. Calculations indicate that differential absorption lidar measurements from space could meet the requirements of the table.

Clouds.- As mentioned above, satellite cloud observations are currently a major source of wind data, but more accurate determinations of cloud-top heights are needed. The changing height of a cloud top is also a measure of the intensity of its upward vertical motion and thus is related to the low-level convergence, subsequent release of latent heat, and eventually to the intensity of rainfall and the degree of storm severity. Thus, improved measurements of cloud-top heights could aid severe-storm prediction in two ways: through improved height assignments to cloud-motion vectors and through more accurate inference of storm intensity. The latter aspect is especially in need of improved measurement techniques because the tops of towering cumulus, which may penetrate the tropopause and be much colder than the surrounding air, yield large height errors when measured by some passive radiometric techniques.

Another cloud parameter that is of value in meteorological analyses is the thermodynamic phase (ice vs. water). Lidar measurements of backscattered polarization can provide information on particle shape and, by inference, on phase. As with cloud height measurements, limited numbers of lidar flights could have a positive impact on operational cloud determinations if passive radiometers (e.g., Kyle, et al., 1978) are co-aligned with the lidar and the lidar data are used to improve the data analysis procedures for the passive sensors (which could be flown more frequently and in geosynchronous orbits).

Summary of Needs and Expected Capabilities

Table II summarizes the resolutions and accuracies required of various parameters for improvements in weather forecasting and the performance that is expected from various lidar experiments. The experiments are described in the section "Candidate Shuttle Lidar Experiments" and in more detail in appendix A where they are grouped according to their probability for success and their complexity; roughly speaking, the smaller the experiment serial number, the greater the feasibility of the experiment. Thus it can be seen that the most feasible lidar experiments (experiments 1 and 2) do not yield direct data on temperature, wind, pressure, or humidity; rather, they are intended to aid current passive methodologies through identifying cloud-top heights and the effects of thin clouds and aerosols on passive profilers. The higher numbered experiments are expected to provide direct measurements of the meteorological parameters with resolutions and accuracies that are often markedly superior to those of current systems. In general, the outstanding advantage expected from the lidar measurements is an ability to provide tropospheric profile data with vertical resolution of order 1 km.

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TABLE I.- MEASUREMENT NEEDS TO AUGMENT THE METEOROLOGICAL DATA BASE[a]

Parameter (b)	Δt, hr	Δx, km	Δz		Accuracy	Remarks
			Troposphere	Stratosphere		
Mid and high latitudes						
Temperature	12 to 24	250 to 500	4 levels (2 km)	3 levels (4 km)	±1 K	
Wind:						
Horizontal	12 to 24	250 to 500	4 levels (2 km)	3 levels (4 km)	±2 m/s	
Cloud motion vector	12 to 24	(c)	----------	----------	±2 m/s	Height must be known to 0.5 km
Vertical	12 to 24	250	4 levels (2 km)	3 levels (4 km)	≈1 cm/s	For individual cloud scale 1 m/s may be useful
Relative humidity	12 to 24	250	4 levels (2 km)	3 levels (4 km)	±30 percent	
Sea surface temperature	12 to 24	250	----------	----------	±1 K	
Pressure:						
Surface (or reference level)	12 to 24	250	----------	----------	±0.3 percent	
Profile	12 to 24	250	4 levels (2 km)	3 levels (4 km)	±0.3 percent	
Tropics						
Wind:						
Horizontal	12 to 24	250	4 levels (2 km)	3 levels (4 km)	±2 m/s	
Cloud motion vectors	12 to 24	(c)	----------	----------	±2 m/s	Height must be known to 0.5 km
Vertical	12 to 24	250	4 levels (2 km)	3 levels (4 km)	≈1 cm/s	For individual cloud scale 1 m/s may be useful
Temperature	12 to 24	500	4 levels (2 km)	3 levels (4 km)	±1 K	
Relative humidity	12 to 24	250	4 levels (2 km)	3 levels (4 km)	±30 percent	
Sea surface temperature	12 to 24	250	----------	----------	±1 K	

[a]Values listed in body of table for Δt, Δx, and Δz apply to inputs for global or hemispheric models. For fine-mesh models, required Δx is 100 km, Δt is somewhat smaller than shown, and Δz can be a factor of 2 finer than that shown.

[b]Additional parameters: cloud, snow, and ice cover; precipitation areas and soil moisture; reflected, scattered, and emitted radiation, albedo and radiation balance.

[c]Needed at 200 km intervals in cloudy regions.

TABLE II.- REQUIRED AND EXPECTED PERFORMANCE FOR LIDAR MEASUREMENTS THAT ADDRESS METEOROLOGICAL OBJECTIVES

Parameter	Required performance								Lidar experiment	Expected performance		
	Global models				Fine-mesh models							
	Δt, hr	Δx, km	Δz, km	Accuracy	Δt, hr	Δx, km	Δz, km	Accuracy		Δx, km	Δz, km	Accuracy
Temperature	12 to 24	500	2 to 4	±1 K	6 to 12	100	1 to 2	±1 K	c_2	2	1	(c)
	12 to 24	500	2 to 4	±1 K	6 to 12	100	1 to 2	±1 K	17	500	2	0.7 to 2 K
Wind	12 to 24	500	[a]2 to 4	±3 m/s	6 to 12	100	[a]1 to 2	[b]±3 m/s	c_1	$c_{\sim}1$	0.15	(c)
	12 to 24	500	[a]2 to 4	±3 m/s	6 to 12	100	[a]1 to 2	[b]±3 m/s	19	0.1	.15	±2 m/s
	12 to 24	500	[a]2 to 4	±3 m/s	6 to 12	100	[a]1 to 2	[b]±3 m/s	20	100	1	±2 m/s
Pressure at reference level	12 to 24	500		±0.3 percent	6 to 12	100	1 to 2	[b]±0.3 percent	15	17 to 100	0.1	0.2 percent
Pressure profile	12 to 24	500	2 to 4	±.3 percent	6 to 12	100	1 to 2		16	500	1	0.1 to 0.5 percent
Relative humidity	12 to 24	500	2 to 4	±30 percent	6 to 12	100	1 to 2	[b]±30 percent	9	50 to 250	2	5 to 35 percent
	12 to 24	500	2 to 4	±30 percent	6 to 12	100	1 to 2		10	10	Column content	±1 percent
									18	160	1	10 percent
Cloud-top height			0.5						1	0.36	0.15	0.15 km
Cloud-droplet phase									3	0.36	0.15	

[a]Cloud motion vector height must be known to 0.5 km.
[b]Better accuracy may be needed for some applications.
[c]Cloud or aerosol measurement to aid passive methodology.

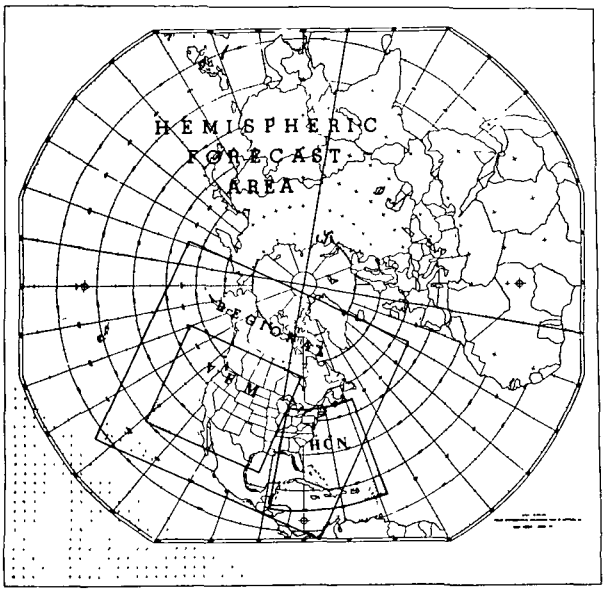

Figure 1.- Horizontal area and sample of grids for several numerical weather prediction models of the U.S. National Meteorological Center. Grid samples for hemispheric, regional, experimental VFM, and HCN models are shown by dot patterns in a corner of each area. (From Shuman, 1978)

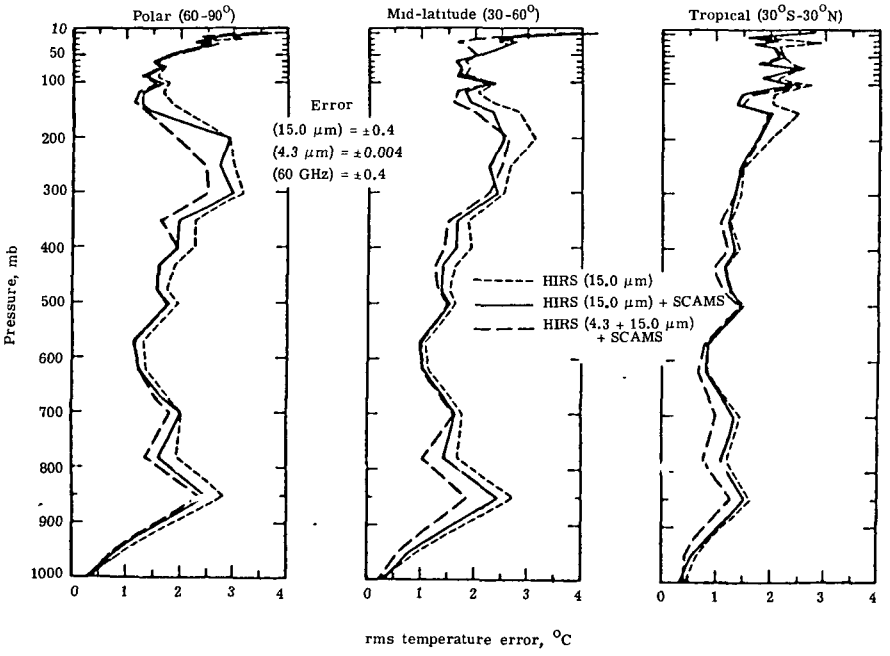

Figure 2.- Comparisons of root-mean-square (rms) temperature errors obtained from simulations using an eigenvector method to process radiances from different channels of infrared and microwave sounding spectrometers. (From Smith and Woolf, 1976)

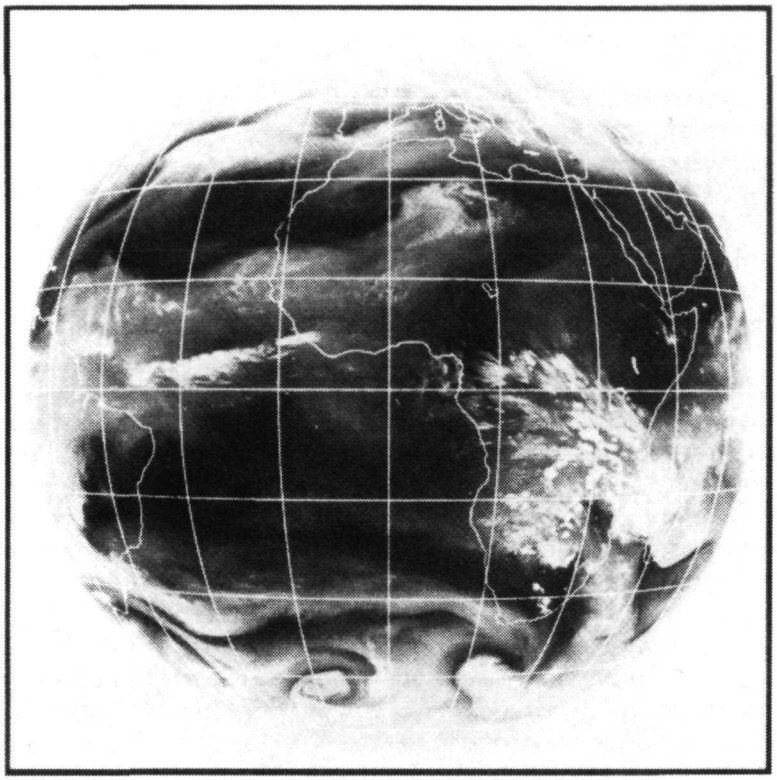

Figure 3.- Typical image of upper-tropospheric water-vapor structure obtained from 5.7 to 7.1 um channel of Meteosat, the European meteorological geostationary satellite. White (dark) indicates relatively large (small) moisture content. (From Morel et al., 1978, courtesy American Meteorological Society)